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14. ABSTRACT
The purpose of this project is to develop optical structures that can be used to perform scaleable quantum logic for Type II quantum computers, using cavity QED. The basis for this concept is the recent demonstration that metallic fractal patterns, when deposited on the surface of a whispering gallery optical resonator can have giant Q-values. This is because the Q of surface plasmon resonances in the metallic fractal patterns multiplies the Q of the optical cavity. Combined Q's of unprecedented size, on the order of 10^{10} -10^{12}, have been inferred from spectroscopic measurements. In addition to higher Q values, the fractal structures also concentrate the optical electric field to volumes on the order of 50 in diameter. This is calculated to produce a vacuum Rabi frequency that is orders of magnitude larger than anything used to date in cavity QED-based quantum computing. This high Q value should allow us to overcome many of the broadening effects present in a solid, as desired to perform solid-state quantum logic.

15. SUBJECT TERMS

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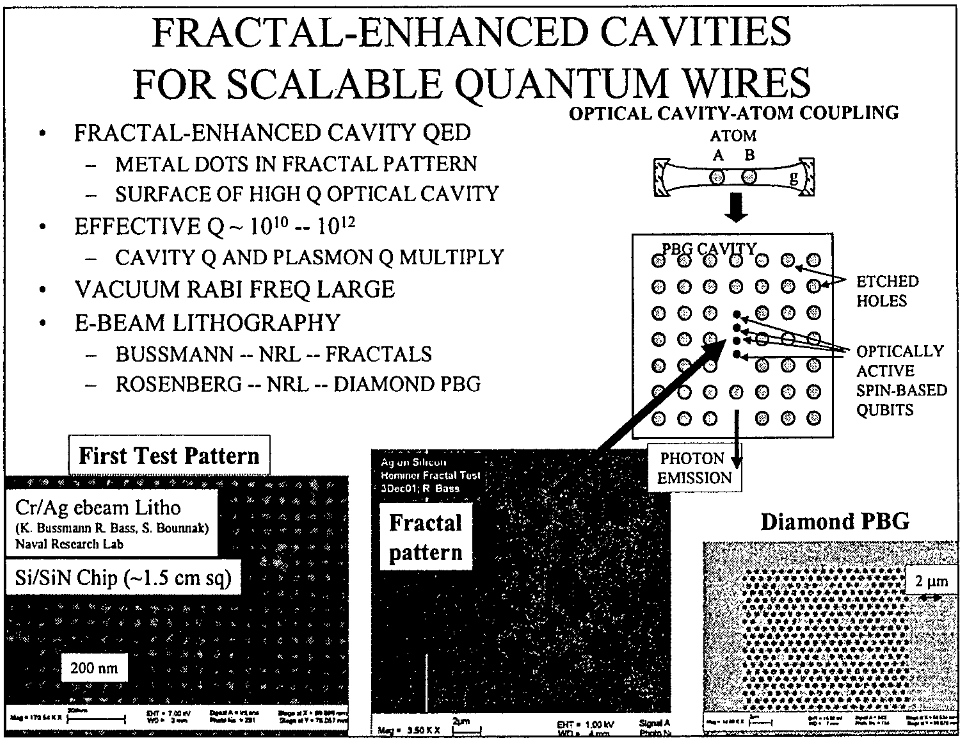
Final report: Fractal-enhancement of photon band-gap cavities for quantum computing and other applications

- PI: Philip Hemmer, Texas A&M University
- co-PI: Robert Armstrong, New Mexico State University
- Objective: Develop arrays of ultra-high Q optical resonators for coupling qubits via cavity QED
- Period of performance: 8/1/02-10/31/05
- DoD lab collaborations: Konrad Bussmann and Armand Rosenberg, NRL
- Relevance and impact: To provide quantum coupling between distant qubits in a solid-state quantum computer. Other applications include ultra-sensitive chemical/biological detectors and single-photon sources

Objective: The purpose of this project is to develop optical structures that can be used to perform scaleable quantum logic for Type II quantum computers, using cavity QED. The basis for this concept is the recent demonstration that metallic fractal patterns, when deposited on the surface of a whispering gallery optical resonator can have giant Q-values. This is because the Q of surface plasmon resonances in the metallic fractal patterns multiplies the Q of the optical cavity. Combined Q's of unprecedented size, on the order of 10^{10} – 10^{12}, have been inferred from spectroscopic measurements. In addition to higher Q values, the fractal structures also concentrate the optical electric field to volumes on the order of 50 nm diameter. This is calculated to produce a vacuum Rabi frequency that is orders of magnitude larger than anything used to date in cavity QED-based quantum computing. This high Q value should allow us to overcome many of the broadening effects present in a solid, as desired to perform solid-state quantum logic.

Period of performance: A no-cost extension was requested to allow NMSU to perform high resolution measurements of local fields near fractal structures.

Relevance and impact: 1. The self-assembled version of fractal-enhanced cavities has been used to demonstrate unprecedented sensitivity for chemical detection. The e-beam fabrication techniques developed here will speed commercialization. 2. Single atoms or molecules potentially make good single photon sources for quantum communication. However to be practical, the photon collection efficiency must be high. Specially designed fractal-enhanced cavities are predicted to be efficient fluorescence collectors.



Summary of relevance to quantum computing and initial nano-fabrication results

By enhancing atom-cavity coupling with plasmon nano-structures, quantum wires can be created. Target material is diamond because of the availability of nitrogen-vacancy (NV) color centers.

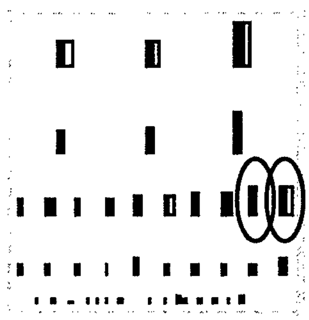
Initial nano-fabricated structures consisted of an array of metal dots showing that the target dot size is achievable. Later, fabrication of fractal patterns was attempted, but due to proximity effects, only magnified versions reproduced the pattern well.

Later PBG structures were fabricated in CVD diamond. More details later.

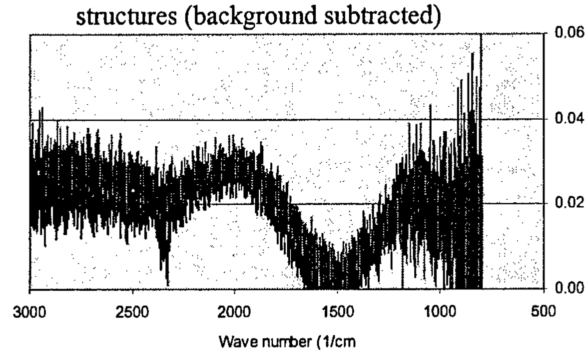
Infrared absorption of nano-fabricated plasmon structures

- Infrared plasmon resonance observed on (NRL) e-beam fabricated nano-structures.

E-beam layout with location of detected structures circled



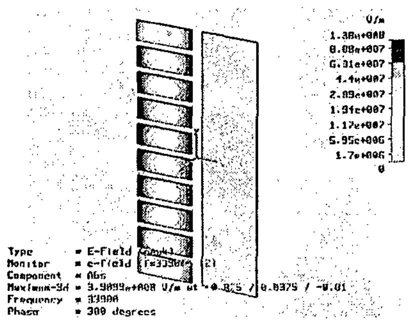
IR absorption signals from circled nano-structures (background subtracted)



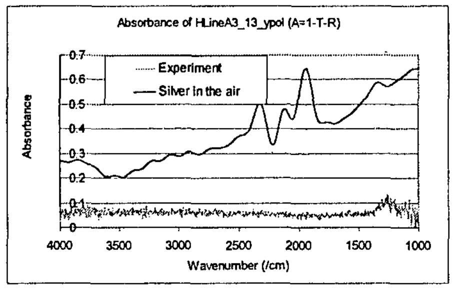
Due to the difficulty of fabricating metallic patterns with feature sizes of less than 5 nm, we have also begun looking at longer wavelength structures. In the mid to far infrared, the wavelengths are a factor of 10 larger than the optical wavelength, so that we only need 50 nm feature sizes. This can easily be reached with standard e-beam lithography. From the applications point of view, there are also advantages to working in this wavelength range, for example, many Air Force sensors prefer this range. Therefore the potential for spin-off applications is actually higher than in the visible. To this end, we have fabricated a number of structures using e-beam lithography. Some of these appear in the e-beam layout on the left. Briefly, they are a series of line, bar, patterns with graded size, so that at least one of each structure will have a resonance in any range that we can probe, from visible to THz. To fabricate the test patterns at NRL, a 100 nm thick SiN membrane suspended on a silicon wafer was used as a substrate. one of these test patterns showed an apparent absorption resonance in an FTIR microscope. The data is obtained by taking the IR signal transmitted through the membrane in the vicinity of the structure and subtracting the signal from the membrane in a nearby location, where no structure was present. The resonances, for two similar structures are shown in . The structures are a vertical array of rectangles with a small gaps between them. One of the structures consists of only the rectangles, and the other consists of the rectangles plus an adjacent long metallic bar. The similarity in the absorption data suggests that the long bar does not contribute to the observed resonance.

Simulation of nano-fabricated patterns and comparison to experiment

- Simulation of metal nano-structures with FTDT (Microwave Studio)



- FTDT simulation of resonances
- Observed resonances appear red-shifted compared to simulation



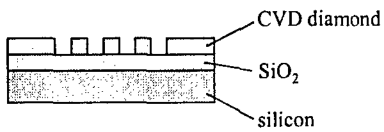
Left: Simulation results showing the electric field distribution, on resonance, for one of the structures in the previous viewgraph. The simulations verify that the adjacent bar does not participate in the resonances as was observed in the experimental data.

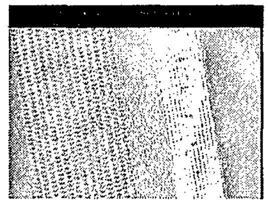
Simulation tool: Microwave Studio

Right: Observed resonances appear red-shifted.

NRL diamond PBG fabrication

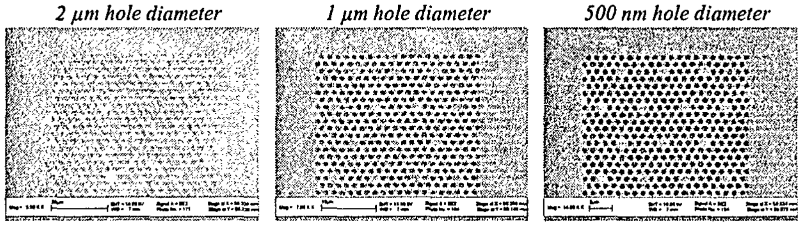
➲ **Photolithography:** Fabricated 1 µm and 2 µm PBG structures with cavity arrays





➲ **e-Beam Lithography:** Fabricated 500 nm, 1 µm and 2 µm PBG structures with cavity arrays

2 µm hole diameter | *1 µm hole diameter* | *500 nm hole diameter*



Details of PBG structure fabrication on CVD diamond.

Starting material was diamond membrane.

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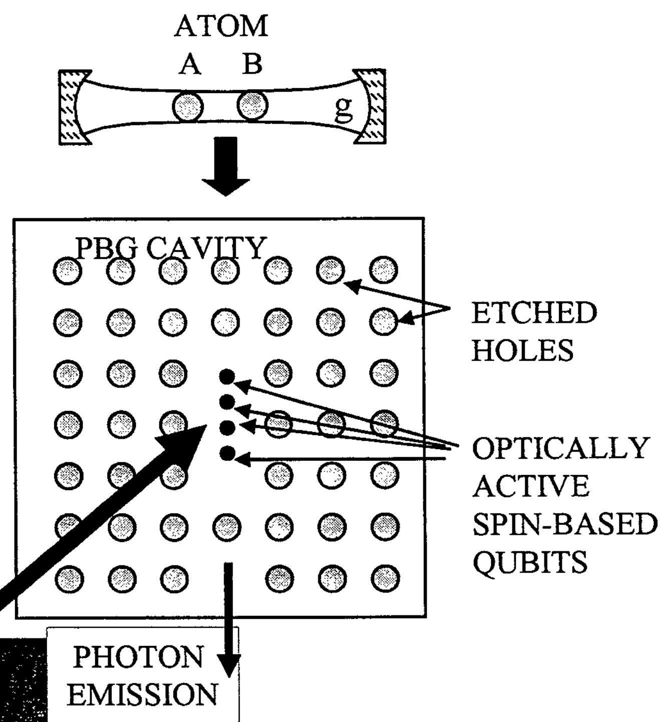
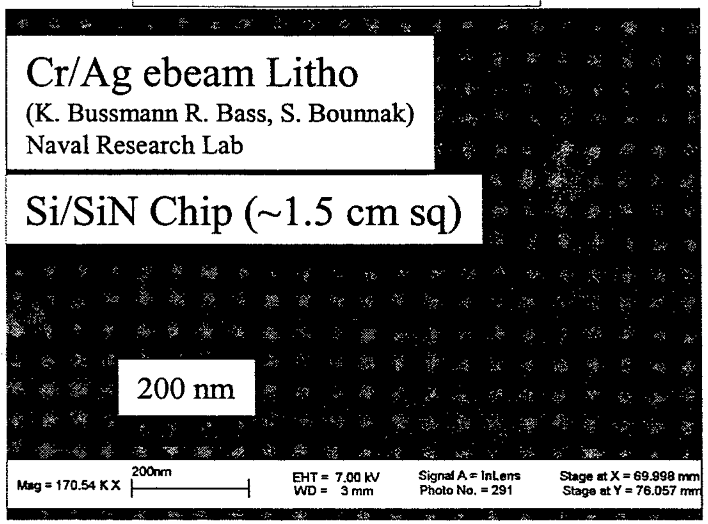
FRACTAL-ENHANCED CAVITIES FOR SCALABLE QUANTUM WIRES

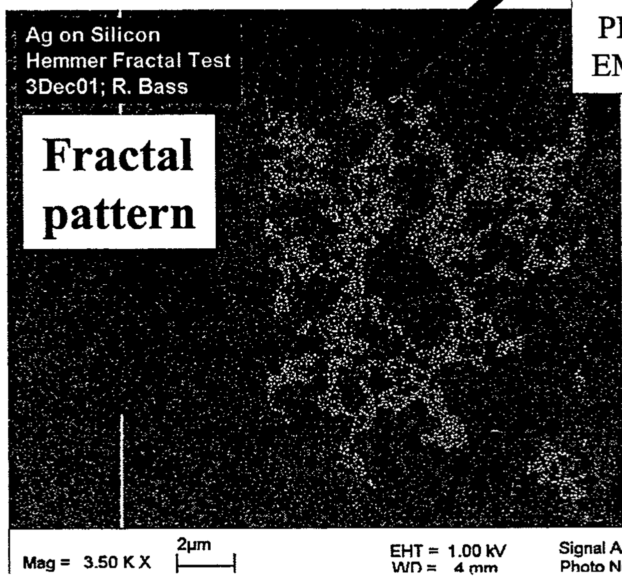
- FRACTAL-ENHANCED CAVITY QED
  - METAL DOTS IN FRACTAL PATTERN
  - SURFACE OF HIGH Q OPTICAL CAVITY
- EFFECTIVE Q ~ 10^{10} -- 10^{12}
  - CAVITY Q AND PLASMON Q MULTIPLY
- VACUUM RABI FREQ LARGE
- E-BEAM LITHOGRAPHY
  - BUSSMANN -- NRL -- FRACTALS
  - ROSENBERG -- NRL -- DIAMOND PBG

OPTICAL CAVITY-ATOM COUPLING

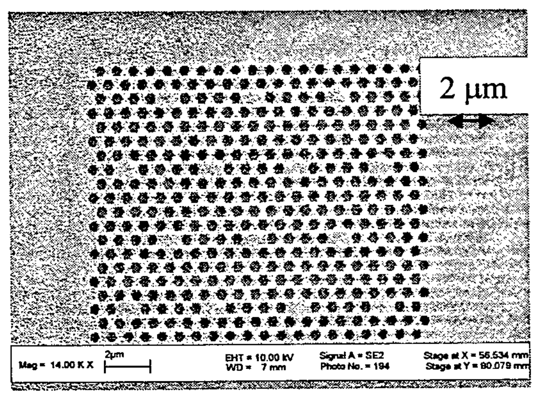


First Test Pattern





Diamond PBG



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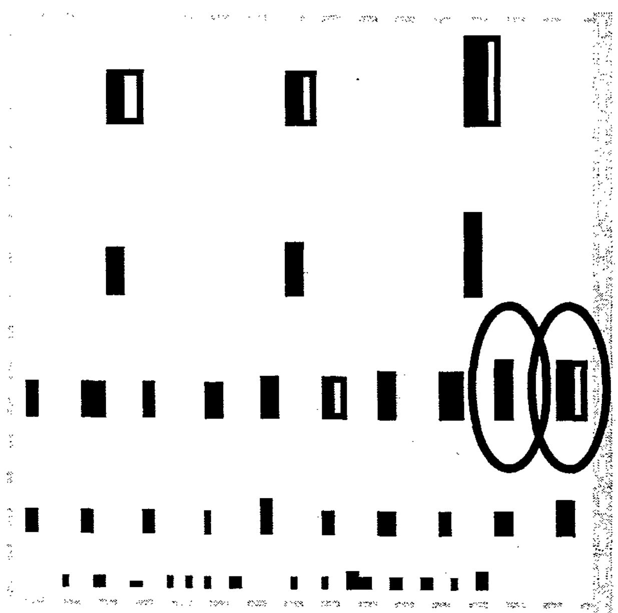

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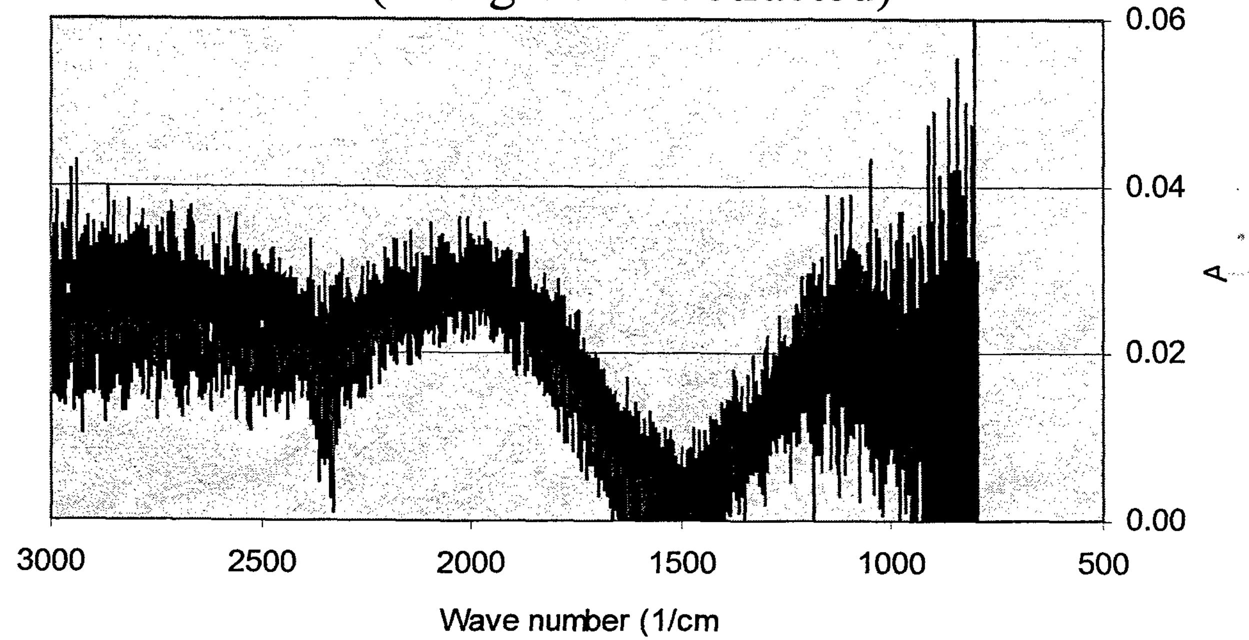

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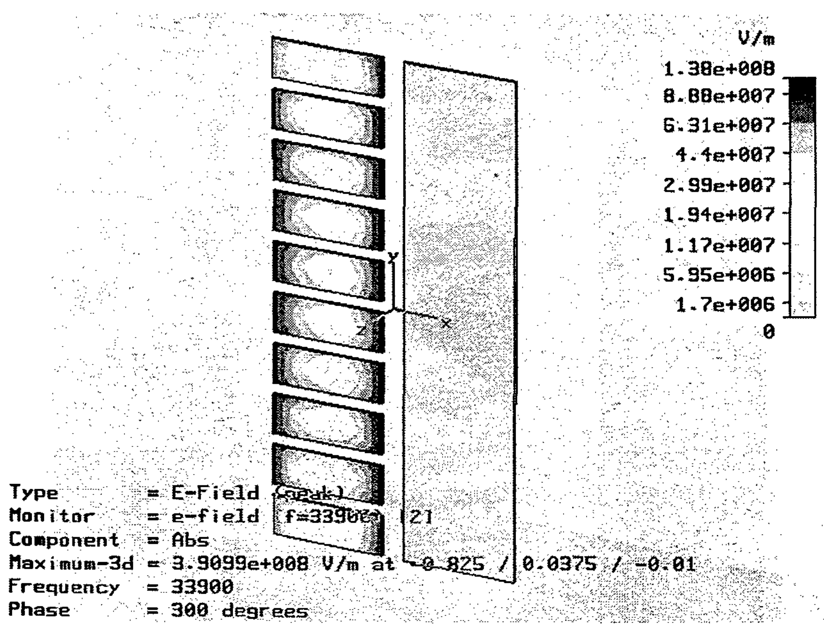

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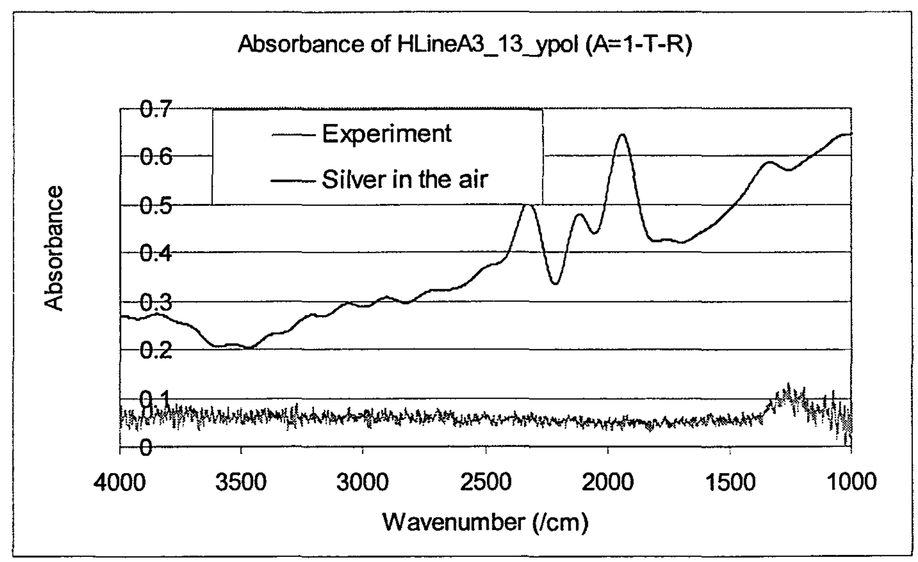

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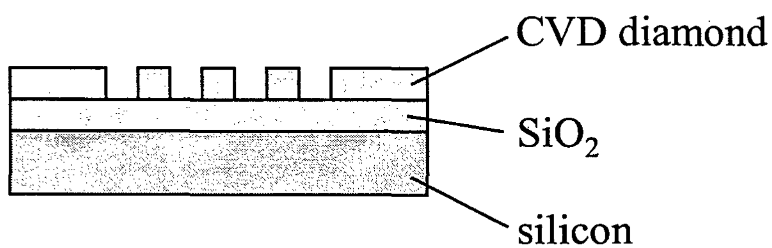
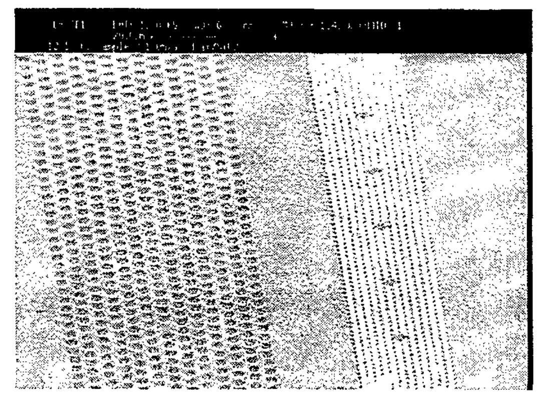
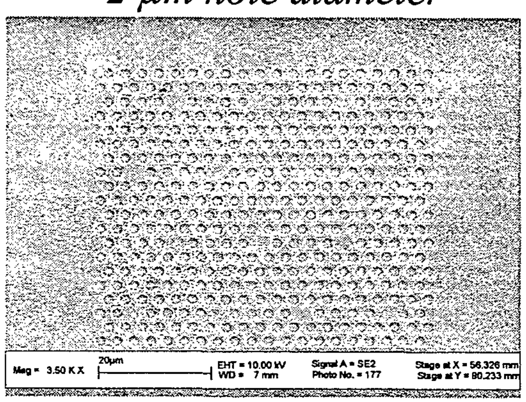


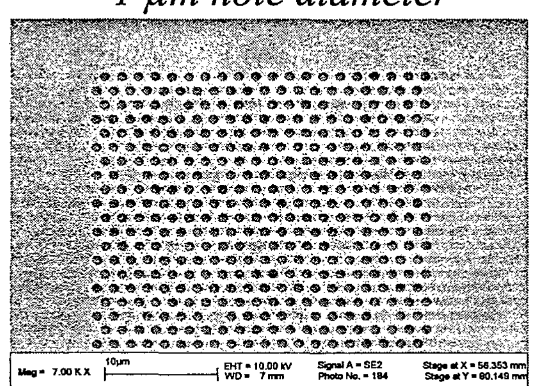


- **e-Beam Lithography:** Fabricated 500 nm, 1 µm and 2 µm PBG structures with cavity arrays

2 µm hole diameter



1 µm hole diameter



500 nm hole diameter